

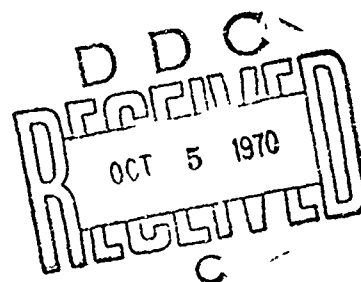
Subcritical Crack Growth in Several Titanium Alloys

T. W. CROOKER, R. W. JUDY, JR., AND L. A. COOLEY

*Strength of Metals Branch
Metallurgy Division*

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NAVAL RESEARCH LABORATORY
Washington, D.C.

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ABSTRACT

Studies of low-cycle fatigue crack propagation in air and in salt water environments and salt water stress-corrosion cracking (SCC) were conducted on several intermediate-to-high strength, very low interstitial oxygen, titanium alloy plate materials. The alloys studied included one sample each of Ti-7Al-2Cb-1Ta and Ti-7Al-2.5Mo, and two samples each of Ti-6Al-4V and Ti-6Al-6V-2Sn. The yield strengths of these alloys ranged from 110 to 150 ksi (77.3 to 105.5 kgf/mm²) and included both as-received and heat-treated conditions. Fatigue and SCC data were obtained from single-edge-notched (SEN) cantilever specimens, and the results were analyzed in terms of crack tip stress-intensity parameters. Most of the alloys investigated exhibited low resistance to low-cycle fatigue crack propagation. The most favorable results were obtained from the Ti-6Al-4V alloys. However, several alloys were highly resistant to environmentally-accelerated crack growth in salt water. Several alloys also showed a correlation between fatigue crack growth behavior in salt water and the threshold stress-intensity for SCC to occur (K_{ISCC}). Examination of fatigue surfaces by electron fractography revealed that the predominant mode of separation was microvoid coalescence, regardless of environment.

PROBLEM STATUS

This report completes one phase of the problem; work is continuing.

AUTHORIZATION

NRL Problems 63M01-25 and 63F01-17
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INTRODUCTION

This report describes studies of low-cycle fatigue crack propagation in air and in salt water environments and salt water stress-corrosion cracking (SCC) in several intermediate-to-high strength titanium alloys. Previous studies of fatigue crack propagation in titanium alloys had revealed two distinct trends with regard to environmentally-accelerated crack growth; several alloys in the as-received (mill-annealed) condition appeared to be nearly insensitive to a salt water environment [1], a rare phenomenon among high-strength structural alloys. However, the alloy Ti-7Al-2Cb-1Ta, which was found to be highly SCC sensitive in salt water, exhibited a distinct threshold strain range level for environmentally-accelerated crack growth in fatigue [2]. Below this critical threshold level there was little environmental sensitivity; whereas above the threshold level there was a sudden, marked acceleration in crack growth rates in salt water.

This present study was undertaken using a variety of titanium alloys, both as-received and heat treated, which offered a range of yield strengths. Experimental procedures were chosen so that the results could be analyzed in terms of linear-elastic fracture mechanics parameters. Stress-intensity thresholds for environmental cracking in salt water (K_{ISCC}) [3] were obtained on each of the materials for correlation with fatigue behavior. Finally, electron fractography studies were conducted on several specimens whose fatigue behavior was considered significant.

MATERIALS

The materials studied in this investigation included one sample each of Ti-7Al-2Cb-1Ta and Ti-7Al-2.5Mo and two samples each of Ti-6Al-4V and Ti-6Al-6V-2Sn. All of the alloys studied were of very low interstitial oxygen content (0.08 wt. percent max.) and all were received as 1 in. (2.5 cm) thick rolled plate stock. The heat treatments given these alloys are shown in Table 1, and the mechanical properties are shown in Table 2.

EXPERIMENTAL PROCEDURES

Low-cycle fatigue crack propagation and SCC experiments were both conducted using side-grooved and single-edge-notched (SEN) cantilever specimens. The Kies equation [5] was used to calculate all stress-intensity values reported. Figure 1 shows the geometry of the notched cantilever

specimens and gives the specific dimensions of the fatigue specimens used for all of the materials except the Ti-6Al-4V sample No. T27. The SCC specimens were of similar geometry and measured 1.0 in. (2.5 cm) deep by 0.75 in. (1.9 cm) thick (side-grooved 0.050 in. (.13 cm) deep on each face) by 7.0 in. (17.8 cm) long. Both the fatigue and SCC specimens for alloy T27 were 0.50 in. (1.3 cm) thick.

Fatigue specimens were cycled zero-to-tension at 6 cpm under constant load. Measurements of fatigue crack length were performed by a slide-mounted optical micrometer focused on the root surface of one side groove. Fatigue specimens were tested in salt water by placing a polyurethane cell around the test section. Distilled water containing 3.5 percent NaCl was continuously pumped through the cell from a reservoir.

SCC specimens were precracked by fatigue and dead-weight loaded to failure. A plastic corrosion cell containing 3.5 percent NaCl in distilled water was placed around the test section. The K_{Isc} value is defined as the maximum stress-intensity level in plane strain which the specimens could sustain for one hour without failure [4].

Fatigue surface features were studied by means of electron microscopy using standard two-stage cellulose-acetate replicas.

RESULTS AND DISCUSSION

The results of this investigation are shown in Figs. 2 through 7, which are log-log plots of fatigue crack growth rate (da/dN) versus stress-intensity factor range (ΔK). Data are shown for both air and salt water environments, and the K_{Isc} level is indicated for each material.

With the exception of mill-annealed Ti-6Al-4V (T27), most of the data presented in these plots follow rather steep slopes. This is indicative of low resistance to fatigue crack propagation, i.e., a small increase in crack tip stress-intensity results in a very large increase in crack growth rates. This observation was also made following a previous investigation of several mill-annealed titanium alloys [1], which had been tested in strain cycling. Furthermore, this behavior does not seem to be mitigated through yield strength/fracture toughness trade-offs. Ti-7Al-2Cb-1Ta (T89) is an intermediate strength, high toughness alloy, and the data for this alloy follow a fifth

power slope. Mathematically this is expressed as follows:

$$da/dN = C (\Delta K)^5$$

where da/dN is the crack growth rate, ΔK is the stress-intensity factor range, and C is a material constant. By way of contrast, high-strength steels possessing high fracture toughness and similar yield strength-to-density ratios follow crack growth relationships varying from second to third powers [6].

Most of the data exhibited slope transitions generally of a sigmoidal shape [7], i.e., a mid-region of shallower slope connecting upper and lower regions of steeper slopes. However, among the heat-treated alloys investigated, the data generally exhibited very steep slopes, as high as tenth power, except in brief mid-regions. These characteristics became more pronounced with increasing yield strength. The difficulties of designing against failure by fatigue crack growth in materials with such characteristics seems obvious. Therefore, for those applications where temperature or weight considerations demand the use of high-strength titanium alloys, potential failure by fatigue crack growth should receive careful consideration.

The environmental aspects of fatigue crack propagation in these titanium alloys are more promising. Several of these alloys showed a near immunity to environmentally-accelerated crack growth in salt water, which is a rare phenomenon among structural alloys. All of the alloys displayed at least a modest degree of environmental sensitivity at high ΔK levels, and most of the alloys displayed little or no environmental sensitivity at low ΔK levels, the one exception being Ti-7Al-2.5Mo (T94) which exhibited environmentally-accelerated crack growth at all ΔK levels examined. The two mill-annealed alloys, Ti-7Al-2Cb-1Ta (T89) and Ti-6Al-4V (T27), showed a correlation between fatigue crack growth behavior in salt water and SCC resistance. In both alloys there was an absence of environmental effects at ΔK levels below K_{Isc} . However, as ΔK approached the K_{Isc} level a sudden dramatic increase in crack growth rates was observed. This corresponds with the crack growth rate threshold behavior previously observed in Ti-7Al-2Cb-1Ta under strain cycling [2]. Among the heat-treated alloys investigated, no correlation was seen between fatigue crack growth behavior in salt water and the K_{Isc} level. This was attributed to two reasons. First, in heat-treated Ti-6Al-4V (T91) the K_{Isc} level closely approached the

fracture toughness levels of the specimens. Thus, the onset of final fracture occurs only slightly above the K_{ISCC} level. Second, in the remaining heat-treated alloys, the air environment crack growth rate curves rose so steeply that rapid rates were attained at $\Delta K = K_{ISCC}$ without any evidence of environmental assistance.

Fatigue surfaces of Ti-7Al-2.5Mo and Ti-6Al-6V-2Sn cycled in both environments were examined by electron fractography using standard two-stage cellulose acetate replication techniques. These two alloys were selected for examination because of the extremely steep slopes exhibited by the data. The predominant surface feature seen in each case was microvoid coalescence (dimpled rupture) for both alloys fatigued in air and in salt water, Fig. 8. Some evidence of striations was observed in regions of low stress-intensity crack growth, Fig. 9. However, this mode was of minor importance overall. Therefore, it appears that fatigue crack growth in these high-strength titanium alloys occurs by a low energy ductile tearing mode which is largely uninfluenced by a salt water environment at ΔK levels below K_{ISCC} .

CONCLUSIONS

The following conclusions have been reached from this investigation:

1. With the exception of one sample of mill-annealed Ti-6Al-4V, the titanium alloys studied in this investigation generally exhibited low resistance to fatigue crack propagation. Crack growth rate (da/dN) data plotted as a function of stress-intensity factor range (ΔK) on log-log coordinates generally followed steep slopes ranging from 4:1 to 10:1.

2. Despite the generally low resistance to fatigue crack growth exhibited by these alloys, there was a marked absence of environmentally-accelerated crack growth in salt water, which is uncommon among high-strength structural alloys. Most notably, Ti-6Al-4V and Ti-6Al-6V-2Sn alloys showed little or no environmental effects, except at higher stress-intensity levels approaching fracture conditions.

3. In two mill-annealed alloys, Ti-7Al-2Cb-1Ta and Ti-6Al-4V, a correlation was seen between environmentally-accelerated crack growth in fatigue and the stress-corrosion cracking parameter K_{ISCC} . Among the remaining heat-treated alloys, no similar correlations were seen.

4. Electron fractographic examination of fatigue surface features in heat-treated Ti-7Al-2.5Mo and Ti-6Al-6V-2Sn revealed the predominant fracture mode to be low energy ductile tearing (microvoid coalescence) for both air and salt water environments at ΔK levels below K_{Isc} . Thus, there is no evidence to suggest that environmental water vapor contributed to the poor fatigue resistance of these alloys.

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REFERENCES

1. Crooker, T. W. and Lange, E. A., "Effects of a 3.5 Percent Sodium Chloride Aqueous Saline Environment on the Fatigue Crack Propagation Characteristics of Titanium Alloys," Applications Related Phenomena in Titanium Alloys, ASTM STP 432, American Society for Testing and Materials, 1968, p. 251
2. Judy Jr., R. W., Crooker, T. W., Morey, R. E., Lange, E. A. and Goode, R. J., "Low Cycle Fatigue-Crack Propagation and Fractographic Investigation of Ti-7Al-2Cb-1Ta and Ti-6Al-4V in Air and in Aqueous Environments," ASM Transactions Quarterly, Vol. 59, No. 2, June 1966, p. 195
3. Brown, B. F., "A New Stress-Corrosion Cracking Test for High-Strength Alloys," Materials Research and Standards, Vol. 6, No. 3, March 1966, p. 129
4. Judy Jr., R. W. and Goode, R. J., "Stress-Corrosion Cracking Characteristics of Alloys of Titanium in Salt Water," NRL Report 6564, July 21, 1967
5. Kies, J. A., Smith, H. L., Romine, H. E. and Bernstein, H., "Fracture Testing of Weldments," Fracture Toughness Testing and Its Applications, ASTM STP 381, American Society for Testing and Materials, 1965, p. 328
6. Crooker, T. W. and Lange, E. A., "Corrosion-Fatigue Crack Propagation Studies of Some New High-Strength Structural Steels," Transactions of the ASME, Journal of Basic Engineering, Vol. 91, Series D, No. 4, December 1969, p. 570
7. Crooker, T. W. and Lange, E. A., "The Influence of Yield Strength and Fracture Toughness on Fatigue Design Procedures for Structural Steels," NRL Report 7036, February 19, 1970

TABLE 1
HEAT TREATMENTS

Alloy	Code No.	Heat Treatment
Ti-7Al-2Cb-1Ta	T89	As received (mill annealed)
Ti-6Al-4V	T27	As received (mill annealed)
Ti-6Al-4V	T91	1725°F/½ Hr/WQ 1000°F/4 Hrs/AC
Ti-7Al-2.5Mo	T94	1725°F/½ Hr/WQ 1000°F/4 Hrs/AC
Ti-6Al-6V-2Sn	T92	1550°F/1 Hr/WQ 1200°F/2 Hrs/AC
Ti-6Al-6V-2Sn	T92	1625°F/1 Hr/WQ 1200°F/2 Hrs/AC

TABLE 2
MECHANICAL PROPERTIES

Alloy	Code No.	0.2% Yield Strength (ksi)	Ultimate Tensile Strength (ksi)	Reduction of Area (%)	Elongation (%)	K _{Isec} (ksi/in.)
Ti-7Al-2Cb-1Ta	T89	110	118	22	11	28
Ti-6Al-4V	T27	116	128	26	12	67 ¹
Ti-6Al-4V	T91	123	135	25	10	70
∞ Ti-7Al-2.5Mo	T94	123	146	8	5	66
Ti-6Al-6V-2Sn (1550°F Anneal)	T92	138	151	16	10	76
Ti-6Al-6V-2Sn (1625°F Anneal)	T92	151	165	12	6	58

1 - Ref. 4

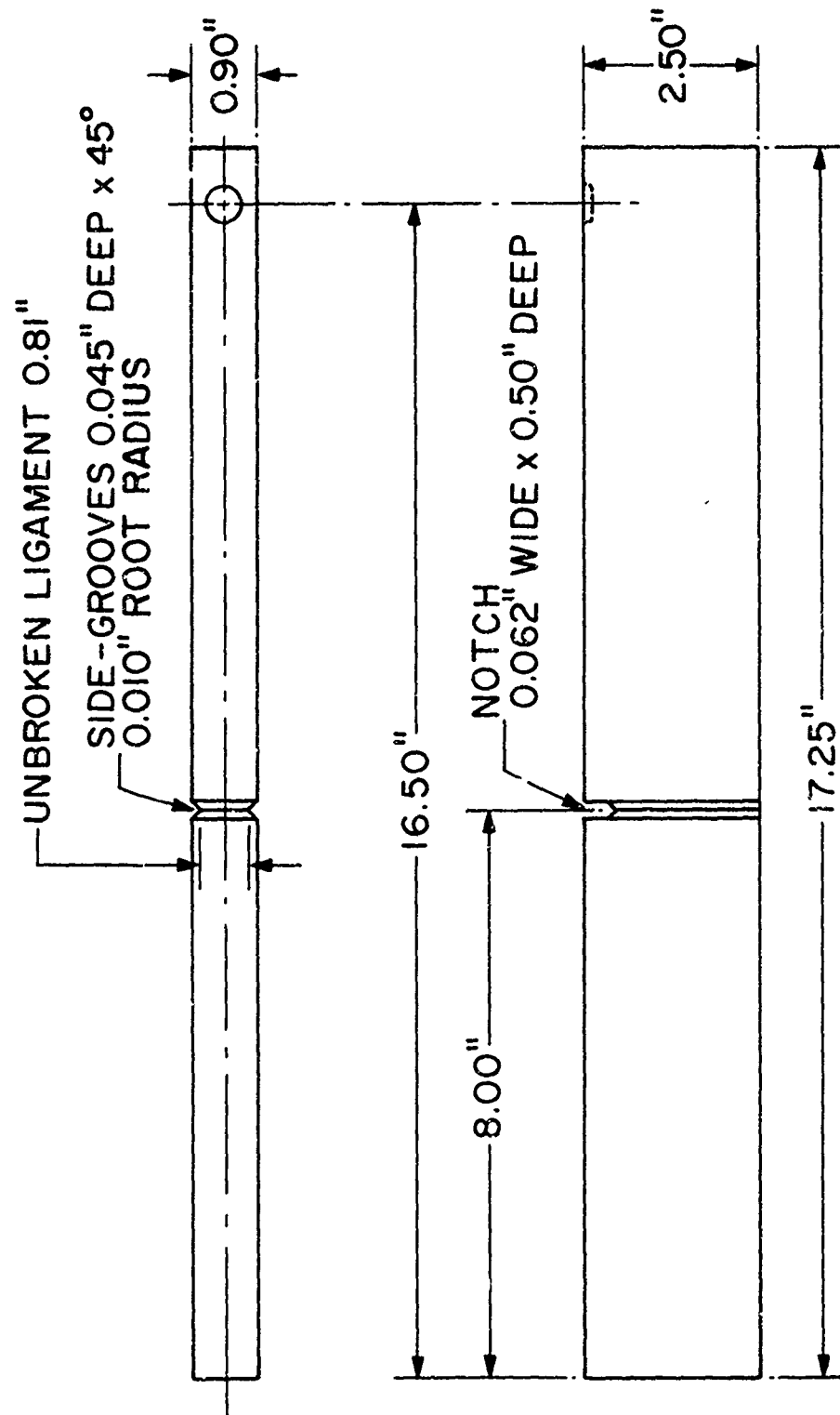


Fig. 1 - Details of the fatigue specimen

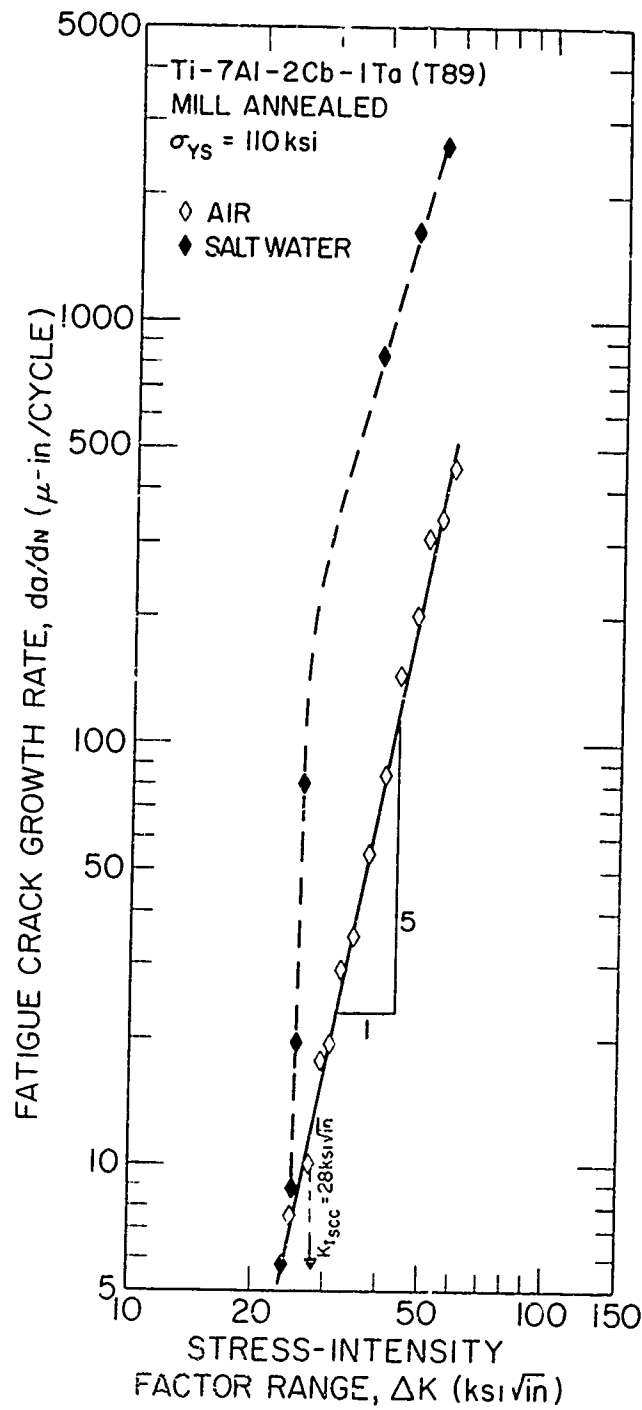


Fig. 2 - Log-log plot of fatigue crack growth rate (da/dN) versus stress-intensity factor range (ΔK) data for Ti-7Al-2Cb-1Ta. The open symbols denote air environment data and the closed symbols denote salt water environment data. The K_{Isc} level is indicated on the ΔK axis.

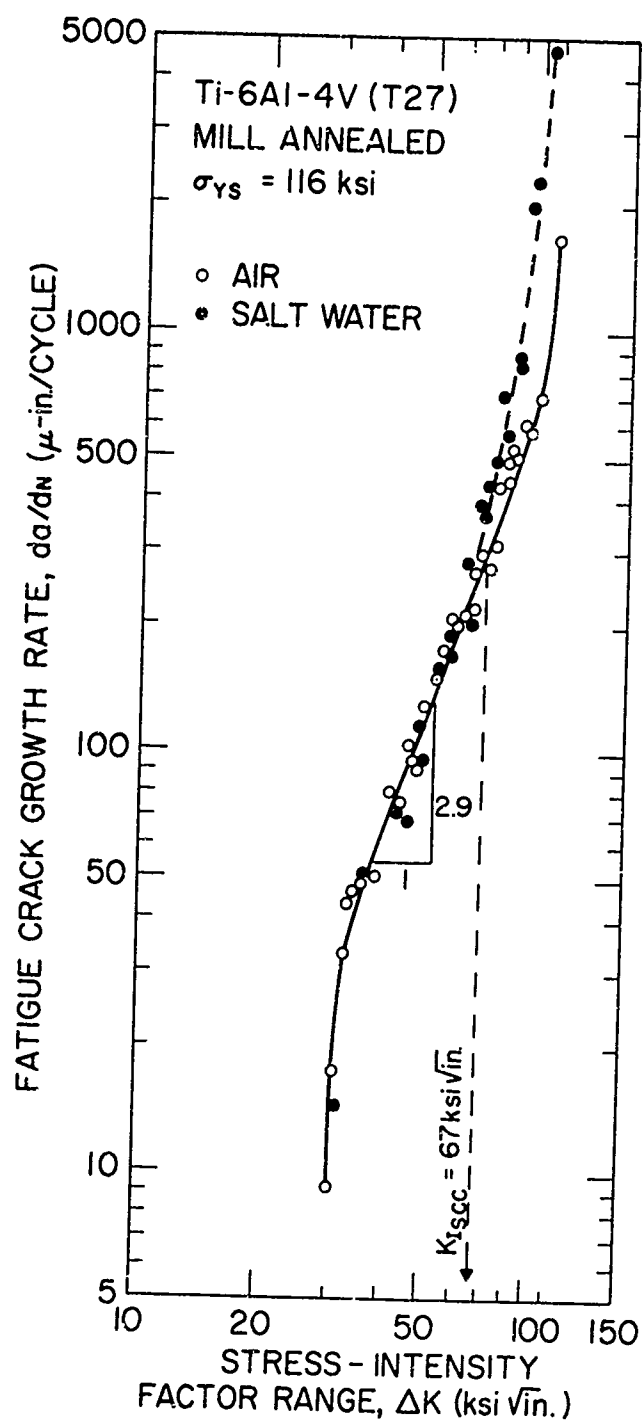


Fig. 3 - Log-log plot of da/dN versus ΔK for mill-annealed Ti-6Al-4V

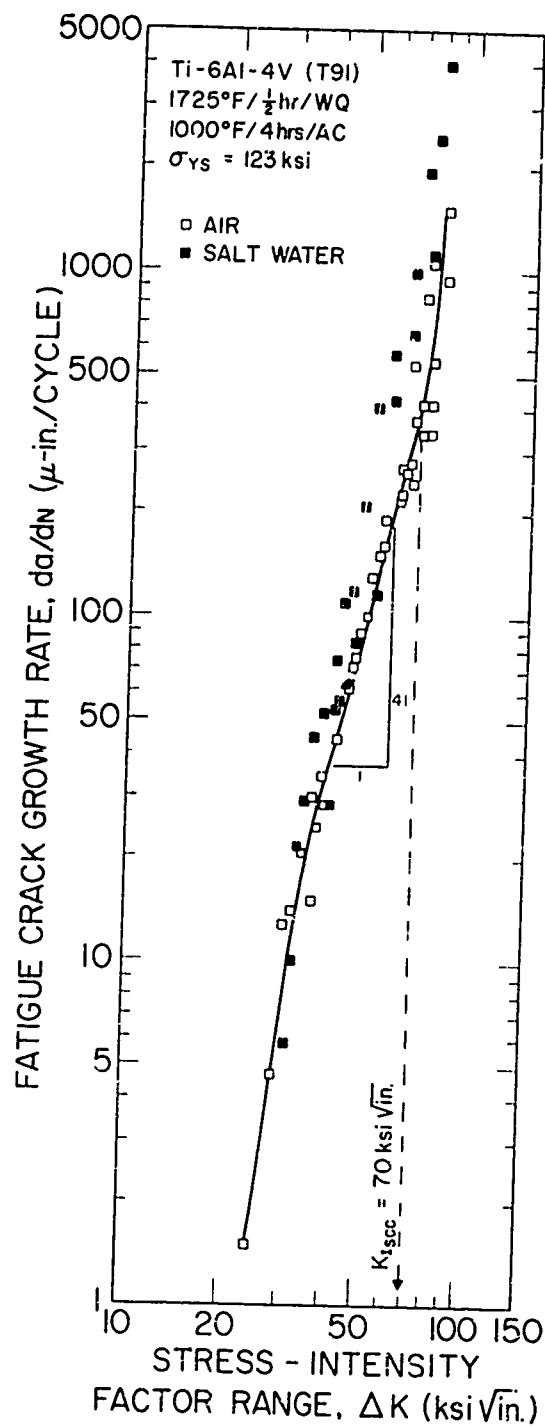


Fig. 4 - Log-log plot of da/dN versus ΔK
 for heat-treated Ti-6Al-4V

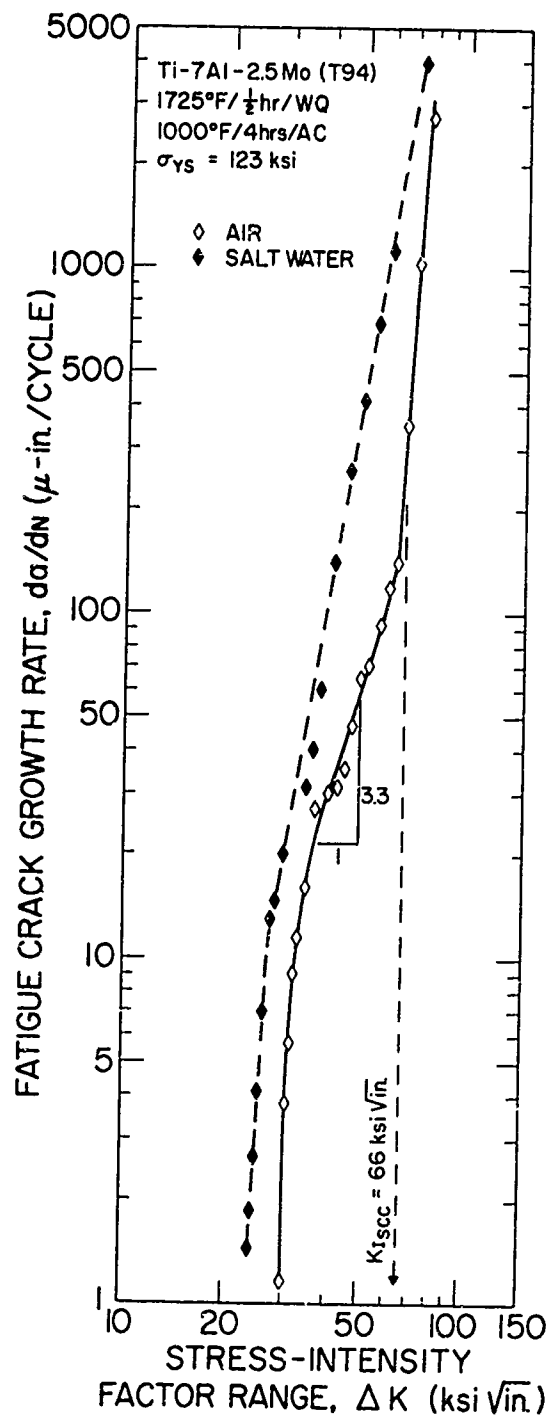


Fig. 5 - Log-log plot of da/dN versus ΔK
 for heat-treated Ti-7Al-2.5Mo

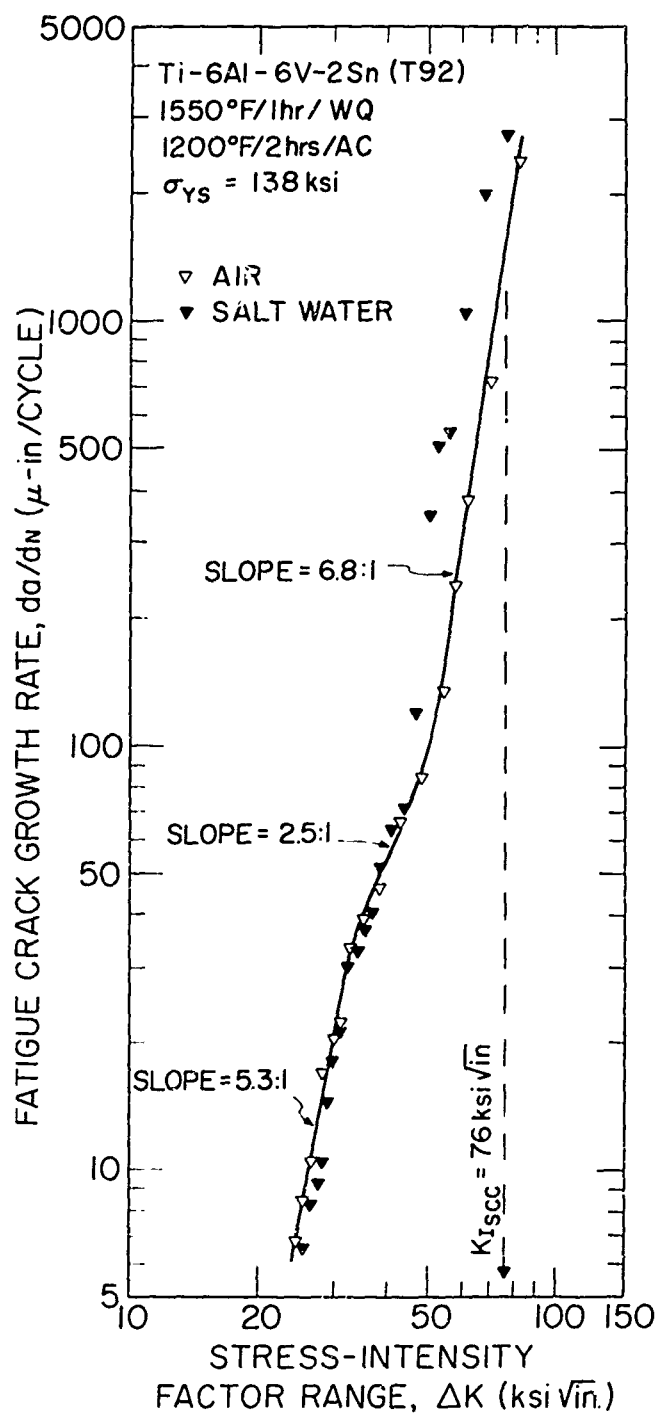


Fig. 6 - Log-log plot of da/dN versus ΔK for heat-treated (1550° F (843° C) anneal) Ti-6Al-4V-2Sn

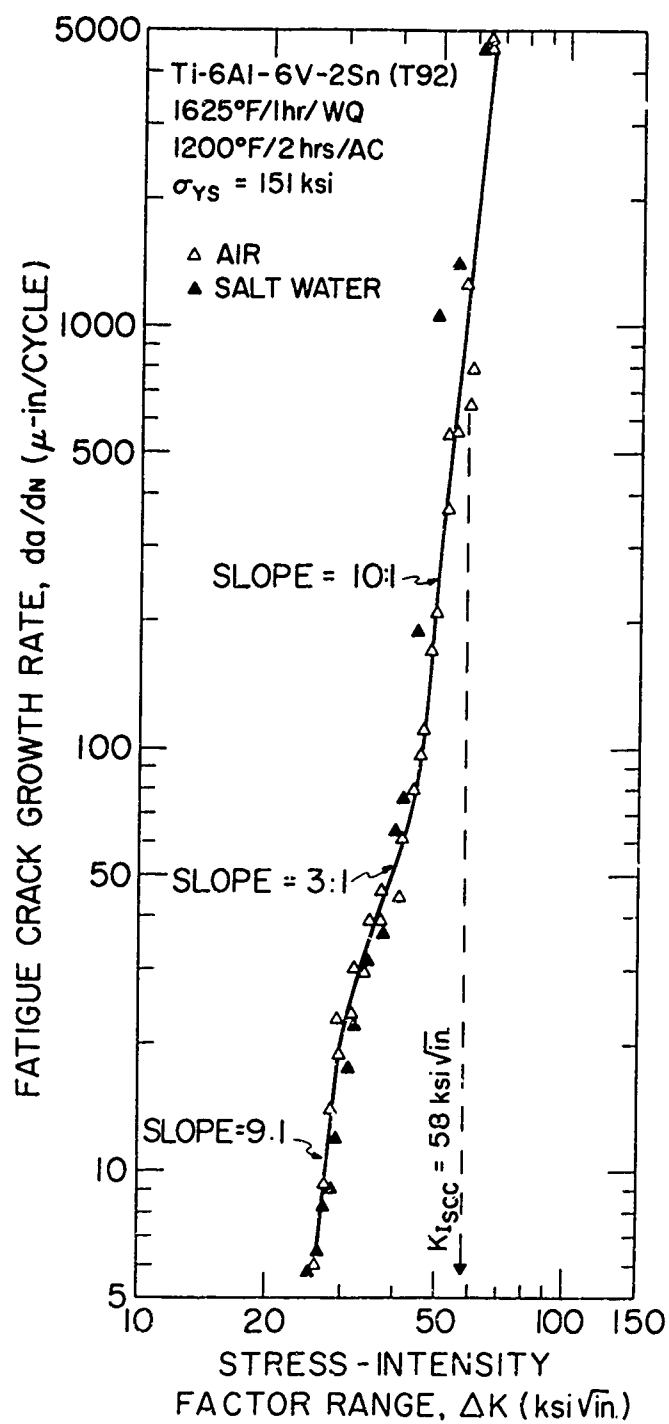


Fig. 7 - Log-log plot of da/dN versus ΔK for heat-treated (1525° F (885° C) anneal) Ti-6Al-6V-2Sn

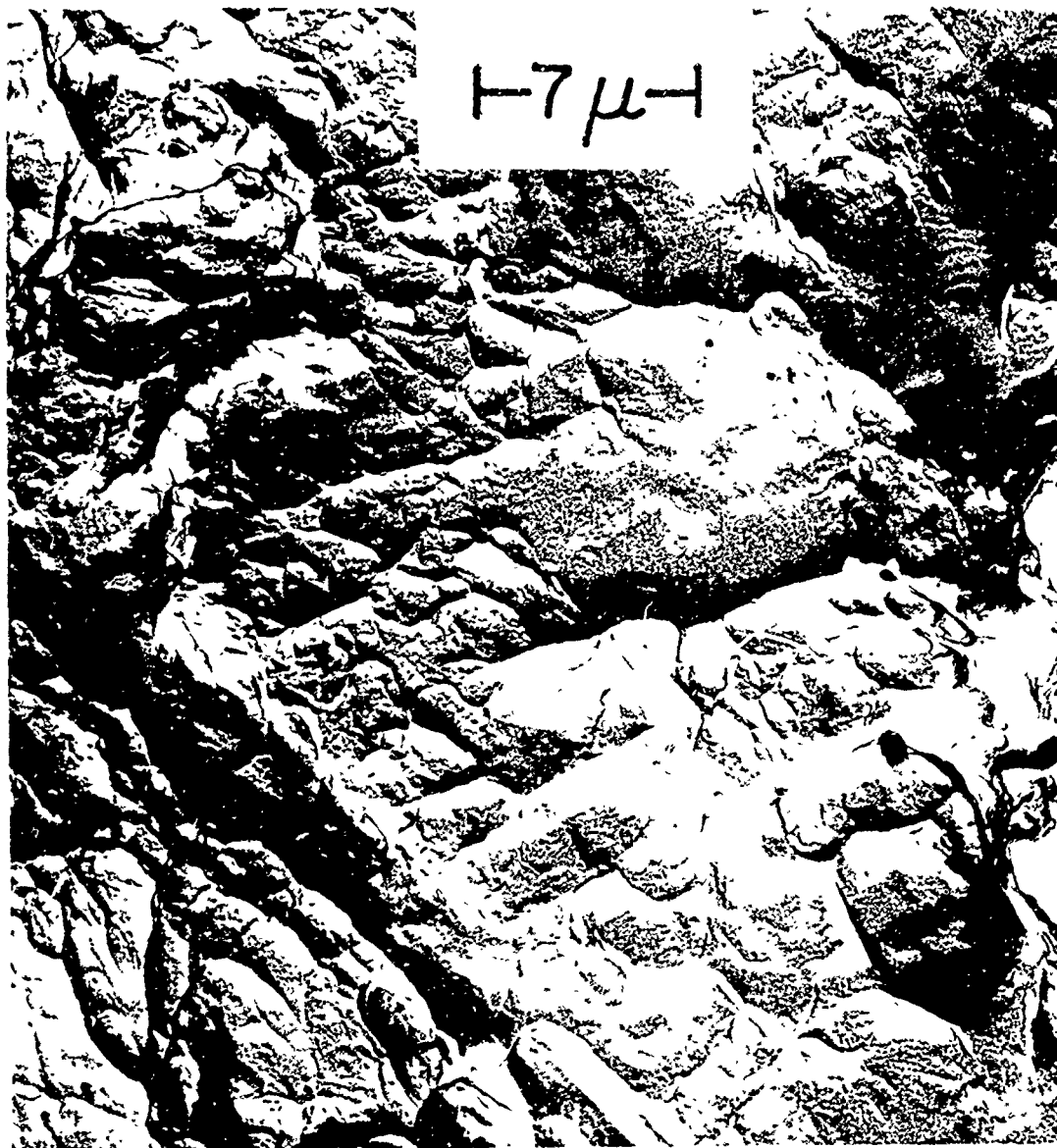


Fig. 8 - Typical features of microvoid coalescence seen on the fatigue surfaces of Ti-7Al-2.5Mo (T94) and Ti-6Al-6V-2Sn (T92) cycled both in air and in salt water. Two-stage cellulose acetate replica.

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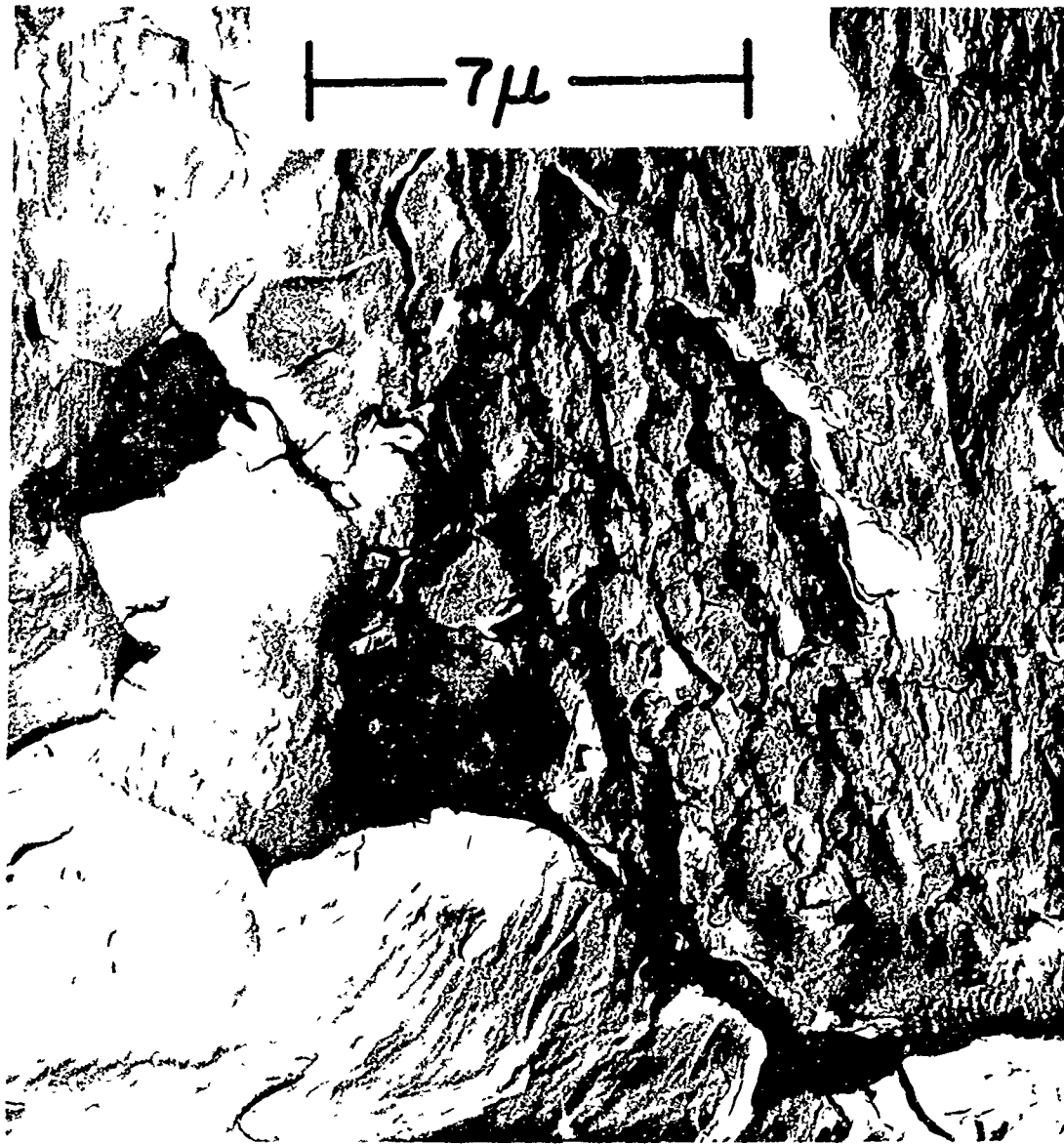


Fig. 9 - Typical combination of striations and microvoid coalescence seen on the fatigue surfaces of Ti-7Al-2.5Mo (T94) cycled in air at low stress-intensity ($\Delta K = 30 \text{ ksi } \sqrt{\text{in.}}$). Two-stage cellulose acetate replica.

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